LIQUID SLOSHING SUPPRESSION EFFECT OF DOUBLE-LAYER ELASTICALLY CONSTRAINED FLOATING PLATE USED FOR PLANT PROTECTION UAVS
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双层弹性约束浮板液体晃动抑制实验研究

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ABSTRACT
Liquid sloshing in pesticide tanks is a major factor affecting the stability of plant-protection unmanned aerial vehicles (UAVs). A double-layer floating plate was developed to improve sloshing suppression. A series of experiments was conducted to measure the sloshing-induced force under horizontal sinusoidal displacement excitation. The results showed that the double-layer floating plate provided superior sloshing suppression over a wider range of liquid depths. An intermediate-sized floating plate also significantly reduced the sloshing-induced force at specific liquid depths, making it suitable for installation within the limited space available inside pesticide tanks.

摘要
药箱内液体晃动是影响植保无人机飞行稳定性的重要因素之一。为提高液体晃动抑制性能设计了双层弹性约束浮板，并实验测量了水平正弦位移激励下的液体晃动力。结果表明双层浮板在更宽的液体深度范围内具有更优异的抑制晃动能力。同时，中等面积的浮板在某些液体深度也可以显著减小晃动力，从而方便布置于药箱的狭小空间。

INTRODUCTION
With the development of agricultural aviation technology, the use of unmanned aerial vehicles (UAVs) has quickly increased over past decade in China. Apart from agricultural information monitoring, fertilizing, seeding, and pest and disease monitoring, one important role of these UAVs are pesticide spraying for their efficient operation and minimal damage properties *(Kartal et al., 2025)*. For the plant protection UAVs, many studies have done such as path planning *(Huang et al., 2023)*, spraying systems design, spraying decisions, downwash airflow *(Fan et al., 2023)*, and droplet drift and deposition *(Kharim et al., 2019)*.

The attitude and velocity of the UAVs may change violently during the operation process involving of take-off, landing, turn around and barrier-avoidance. So, the liquid sloshing occurs almost inevitably in the pesticide tank. Sloshing is the motion of the free liquid surface. Most of the time during the pesticide spraying process, the pesticide container has a free liquid surface. So, the liquid sloshing is prone to occur when the attitude and velocity of the tank change. The fluid sloshing can introduce large complex disturbance forces and torques and the center of mass shifting, which affect the position and attitude stability of the UAVs. Not only is it difficult to ensure the accuracy of the trajectory and spraying, but also it endangers the safety of the drone. The liquid sloshing in plant protection UAVs has attracted the attention of many researchers *(Sun et al., 2024)*. Apart from the reasonable shape design of the container *(Ahmed et al., 2022)*, one effective way to suppress liquid sloshing is to install rigid or flexible bulkheads *(Liu et al., 2025; Park et al., 2025; Raja et al., 2023; Ren et al., 2023; Raja et al., 2023)*, grilles *(Li et al., 2017; Ru et al., 2023; Yu et al., 2020)*, perforated baffles *(Nimisha et al., 2022; Wang et al., 2023; Wang et al., 2026)*, and other similar structures inside the vessel.

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To reduce liquid impact load induced by sloshing, moving baffles that contain a spring system were introduced *(Kim et al., 2018)*. A kind of floating baffle that can move up and down along two slide rails was adopted to reduce sloshing at different liquid levels *(Yu et al., 2017; Zhang et al., 2025)*.

Bulkheads or baffles that placed horizontally or vertically can suppress the liquid sloshing effectively, especially in the case of multilayer boards. However, the mass of these boards will definitely reduce the payload of the UAVs. For the multi-rotor electric drones that are widely used in plant protection operation, it's definitely something to keep in mind. Based on this consideration, the author used low-density foam to make the baffle and introduced an elastically constrained floating plate to suppress liquid sloshing in the pesticide tank of plant protection UAVs *(Zheng et al., 2023)*. The experimental results show that the liquid sloshing suppression capability is improved to some extents and the sloshing suppression effect depends on the relative location between the free surface and the floating plate.

Based on this discovery, the research is further extended and a double-layer elastically constrained floating plate is proposed in this article. A series of experiments are conducted to investigate the liquid sloshing suppression performance of this new structure, and the underlying physical mechanism is strived to explore.

MATERIALS AND METHODS

Experimental setup

The experiment is carried out on a 6-degree-of-freedom motion simulator that moves horizontally in a sinusoidal function form to drive the liquid in a rectangular tank to slosh, as shown in Fig. 1.

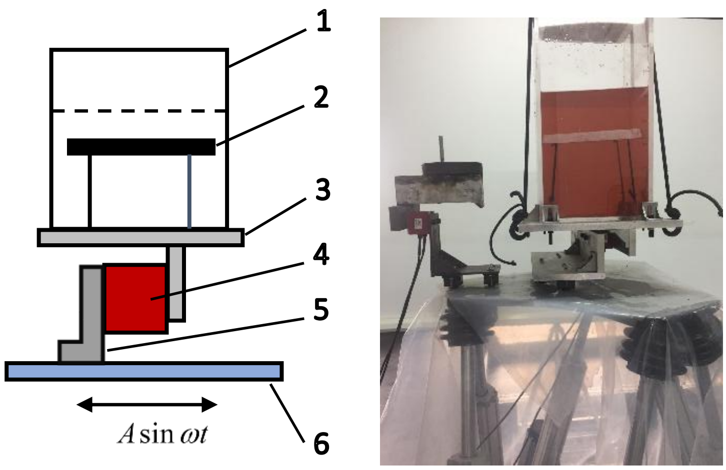


Fig. 1 - Schematic (left) and onsite photo (right) of experiment setup

1-tank; 2-elastically constrained floating plate; 3-T-shaped bracket; 4-force sensor; 5-L-shaped bracket; 6-movement simulator

The internal dimensions of the transparent acrylic rectangular tank are 230 × 220 × 400 mm (length× breadth× height), and the thickness of the walls is 10 mm.

The sloshing force is measured by a force sensor that based on the stress-strain relation and a corresponding dynamic strain instrument. The inertial force of the tank and the T-shaped bracket is synchronously measured by a specially designed mass block and another force sensor, and removed in following data processing procedure.

The square-shaped floating plate is made of foam material with a thickness of 20 mm. Three different side lengths of the square, i.e.,100, 150 and 200 mm, are adopted in different cases. Corresponding to these three lengths, the ratio of the area of the floating plate to the cross-sectional area of the tank is 20%, 45% and 79% respectively.

The floating plate is connected to the fixed point on the bottom of the tank with elastic rubber ropes. The elasticity recovery coefficient of the rope is determined as 67 N/m after undergoing tensile tests on a testing machine and fitting. The length of the rubber rope is set to 150 mm for the single-layer floating plate, and the lengths of the two rubber ropes are both 75 mm for the series-connected double-layer floating plate. In other words, the total length of the rope is the same for these two kinds of floating plate.

The liquid used in the experiment is tap water. Some paint is added in the water for the convenience of observation.

Experimental cases

Basic conditions

During the spraying process, the liquid inside the pesticide tank of the plant protection drone is constantly consumed, causing the liquid depth to change. To reflect the liquid sloshing suppression ability of the floating plate at different liquid depths, six liquid depths are considered, namely 100 mm, 150 mm, 200 mm, 250 mm, 300 mm and 350 mm.

The natural frequency of the liquid depends on the tank's length and the liquid depth that can be calculated according to the formula listed as follows *(Ibrahim, 2005)*.

$$\omega_n = \sqrt{g\frac{n\pi}{l}\tanh\frac{n\pi h}{l}} \tag{1}$$

where:

ω_n is the n-th order natural frequency of the liquid, [rad/s];

n is the order of the liquid sloshing frequency, n = 1,2,3….;

g is the acceleration due to gravity, [m/s^2], and g = 9.8 m/s^2;

l and h are is the tank length in the direction of excitation and the liquid depth respectively, [m].

The first-order natural frequency plays a critical role in liquid sloshing. So, experimental conditions focus on the vicinity of the first-order natural frequency in this article. The first-order natural frequency f in Hz is adopted in experiments for convenience. According to the formula (1), the first natural frequencies of six depths above-mentioned are 1.725 Hz, 1.811 Hz, 1.834 Hz, 1.839 Hz, 1.841 Hz and 1.841 Hz, respectively.

The horizontal displacement of the motion simulator, denoted by $x(t)$, is expressed as:

$$x(t) = A\sin(\omega t) \tag{2}$$

where:

A is the amplitude of the horizontal displacement, [m];

ω is the excitation frequency generated by the motion simulator, [rad/s];

t is the time of motion, [s].

After many trials, A = 5 mm is chosen as the excitation amplitude. Either small amplitude or violent sloshing can be got by changing excitation frequency at this amplitude. The duration time for each case is set to 60 seconds.

To get different amplitude sloshing, the excitation frequency is adopted as 0.5f - 1.2f (with an interval of 0.1f). It should be noted that the sloshing phenomenon is more severe when approaching the first natural frequency, so two excitation frequencies are further introduced, i.e., 0.95f and 1.05f.

In the subsequent experiments, the liquid depth and excitation frequency are used as basic conditions. In other words, the sloshing forces at different liquid depth and excitation frequency will be measured for all kinds of floating plate. The number of floating plate layers and the area of the floating plates are the focus of this research, so they are served as control variables.

The number of layers

In previous studies *(Zheng et al., 2003)*, only one elastically contained floating plate is used which has been described in detail. Based on this layout, another floating plate and elastic ropes are added. Namely, two floating plates are used which connect with rubber ropes and arrange in a series form. Here, the former is called as a single-layer floating plate and the latter is named as a double-layer one. At this stage, the focus is on examining the impact of the number of floating board layers on the ability to suppress sloshing. So, the area of the floating plate keeps as same, and the area ratio of floating plate is 79% in both single-layer and double-layer floating plate.

To analyze the effect of the different floating plate arrangement on suppressing liquid sloshing, experiments were also conducted to measure the liquid sloshing force without any floating plate.

The areas of the double-layer floating plate

The cross-sections of the container may change at different position and there are accessories such as pumps and tubes in the pesticide tank of plant protection UAVs. It means that the space available may be limited for arranging the floating plate. Therefore, a smaller floating plate may be needed in practical applications.

Based on the first stage experiment, the floating plate with different sizes are used in the double-layer floating plate to analyze the influence of area on the sloshing suppression effect. In the first case, both the upper and the lower floating plate have the same area ratio. In other words, the areas of two floating plates change synchronously. Three area ratios are adopted, i.e., 20%, 45% and 79%. In the second case, the area ratio of the upper floating plate keeps as 79%, but the lower one has the area ratio of 20%, 45% and 79%, respectively.

RESULTS

The effect of the number of layers

At each liquid depth, horizontal displacement excitations with different frequencies were applied to the tank without any floating plate, with the single-layer floating plate, and with the double-layer floating plate. The liquid sloshing force was measured using the strain-type force sensors, and the results are shown in Fig. 2. Where, three configurations are indicated as 'without plate', 'single-layer' and 'double-layer', respectively.

The blue curve shown in the figure is the theorical liquid sloshing force in a rectangular tank that given in following formula *(Ibrahim, 2005)*

$$F = A\omega^2 \rho lwh \left\{ 1 + \sum_{n=1}^{\infty} \left[\frac{8\tanh\dfrac{(2n-1)\pi h}{l}}{\dfrac{(2n-1)^3 \pi^3 h}{l}} \frac{\omega^2}{\omega_n^2 - \omega^2} \right] \right\} \tag{3}$$

where: F is the sloshing force, [N];

ρ is the density of the liquid, [kg/m³], and the density of water is 1000 kg/m³;

w is the liquid width, [m].

The other variables and values have already been given earlier.

It needs to be pointed that the theoretical sloshing force is given based on linear theory. The sloshing force tends towards infinity at the natural frequency, and it isn't been fully drawn for clarity.

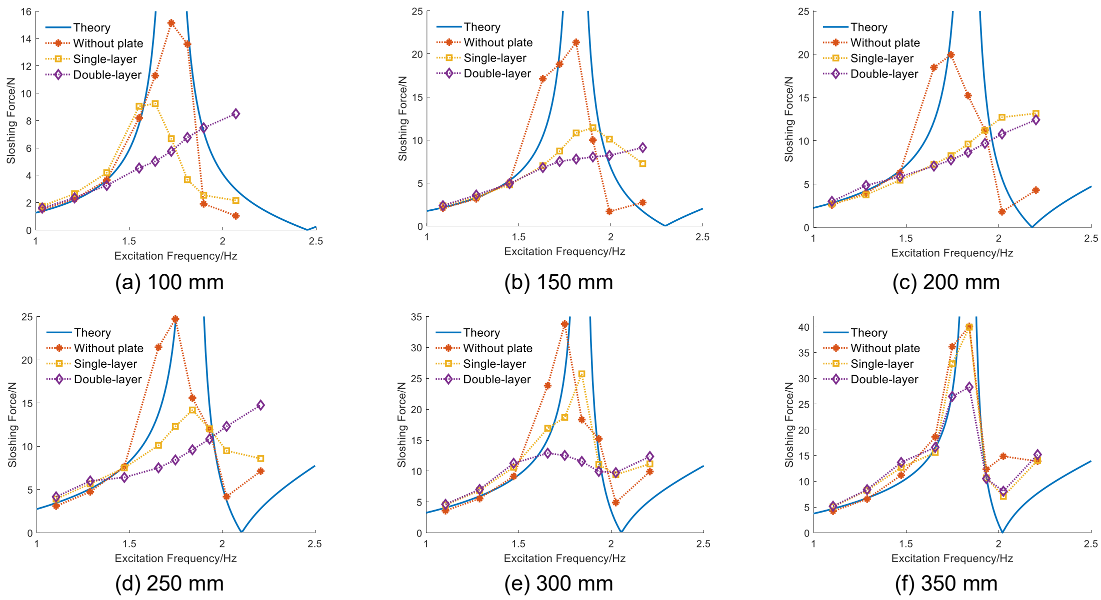


Fig. 2 - Liquid sloshing force at different liquid depths

It can be seen that the sloshing suppression effect of single-layer and double-layer floating plates varies at different liquid depths. Therefore, the following discussion will be based on the liquid depth.

When the excitation frequency is 0.6, 0.7, and 0.8 times the first-order natural frequency (i.e. 0.6 f, 0.7 f and 0.8 f), the experimental values agree well with the theoretical ones at all liquid depths, as shown in the figure. The reason is that the amplitude of liquid sloshing is relatively small at these excitation frequencies, meeting the small-amplitude sloshing assumption in formula (2). This also indicates that the sloshing force measurement system in this article is reasonable and reliable.

Moreover, it also can be seen that the sloshing force with a single-layer or double-layer floating board is not significantly different from that without any floating board at all liquid depths and these three excitation frequencies. This implies that the float plate is not very effective in suppressing slight movements of the liquid. Therefore, the main concerns are put on the large amplitude sloshing of the liquid near its natural frequency.

Fig. 2(a) shows the liquid sloshing force when the liquid depth is 100 mm. It can be seen that the sloshing force decreases from 11 N to 9 N and 5 N for without plate, single-layer and double-layer floating plate at 0.95 f. When the excitation frequency is equal to 1.0 f, the sloshing forces under these cases are 15N, 7N and 5N, respectively. The elastic rope length of the single-layer floating board is 150 mm, which is greater than the liquid depth. Therefore, the floating board remains in a floating state and cannot effectively suppress the movement of the liquid. However, the elastic rope length of the lower section of the double-layer floating plate is 75 mm, which is less than the depth of the liquid. The elastic rope is stretched by the buoyancy of the lower floating plate. On one hand, the lower floating plate rises to a position near the free liquid surface. On the other hand, the movement of the lower floating board is restricted by the elastic cord. As a result, neither the floating board nor the free liquid surface can move violently in the vertical direction. In other words, the liquid can hardly move freely, but only moves horizontally along with the tank. Therefore, the sloshing force for the double-layer floating plate exhibits characteristics of an inertial force that increases with the increase of the excitation frequency.

When the liquid depth equals the rope length of the single-layer floating plate, i.e., 150 mm, the elastic rope begins to bear the tension generated by the upwards movement of the plate. It means that the elastic rope can rebound to some extent if large amplitude liquid sloshing occurs. Therefore, it exhibits relatively good sloshing suppression effect near the natural frequency. As for the double-layer floating plate, the lower plate is completely submerged in the liquid and the lower elastic rope is fully stretched at this depth. So, the sloshing of the liquid below the lower plate is completely suppressed. Meanwhile, the small amount of liquid above the lower floating plate hardly moves vertically due to the suppression of the upper floating plate. Thus, the sloshing force still maintains the inertial force characteristics.

Both single-layer and double-layer floating plate are submerged below the free liquid surface when the liquid depth is 200 mm. The elastic rope is fully stretched for both cases so that the liquid sloshing is effectively suppressed. The sloshing force is about 8 N at 0.95 f, which is 40% of that without any plate. The sloshing forces for the two kinds of floating plate exhibit an inertial force characteristic and are almost the same except for a few frequencies.

When the depth is 250 mm, the sloshing forces exhibit characteristics similar to those at the liquid depth of 150 mm. However, the formation mechanism of the sloshing force for the single-layer floating plate is different. The floating plate is totally submerged and the elastic rope is fully stretched. Thus, the liquid below the plate moves with the tank and the sloshing force with inertial force characteristics generates. But the liquid on the floating plate (about 50 mm deep) can move freely. This part of the liquid will experience significant oscillation when the excitation frequency is close to the natural frequency, resulting in relatively large dynamic forces. For the double-layer floating plate, both segments of the elastic rope are fully stretched. The upper floating plate is closer to the free liquid surface, and all the liquid cannot move freely. Therefore, the sloshing force still remains in the form of the inertial force. As for the magnitude of the sloshing forces at natural frequency, they are 25 N, 14 N and 8 N for without plate, single-layer and double-layer floating plate, respectively. In other words, the sloshing force can be reduced about half or two-third by single-layer or double-layer floating plate.

When the liquid depth reaches 300 mm, the maximum sloshing forces for three cases are 33 N, 25 N and 12 N, respectively. The suppression strength and effective range of the double-layer plate are both greater than those of the single-layer plate.

The sloshing forces at all frequencies for the single-layer floating plate are basically the same as those without plate when the liquid depth is 350 mm. It implies that the sloshing suppression capability is almost completely lost. Although the double-layer floating plate still functions, the range is limited to a narrow frequency band. The reason is that the floating plate locates a deeper position below the free surface and the liquid on the floating plate is no longer restricted by the floating plate.

Overall, the double-layer floating plate has a wider effective range and better suppression capability than the single-layer floating plate. To intuitively understand the sloshing suppression effect of the floating plate, the typical waveforms of the free liquid surface under different excitation frequencies are shown in Fig.3.

Where, the liquid depth is 250 mm and the excitation frequency is 0.7 *f*, 0.8 *f*, 0.9 *f*, 1.0 *f*, 1.1 *f*, and 1.2 *f*, respectively.

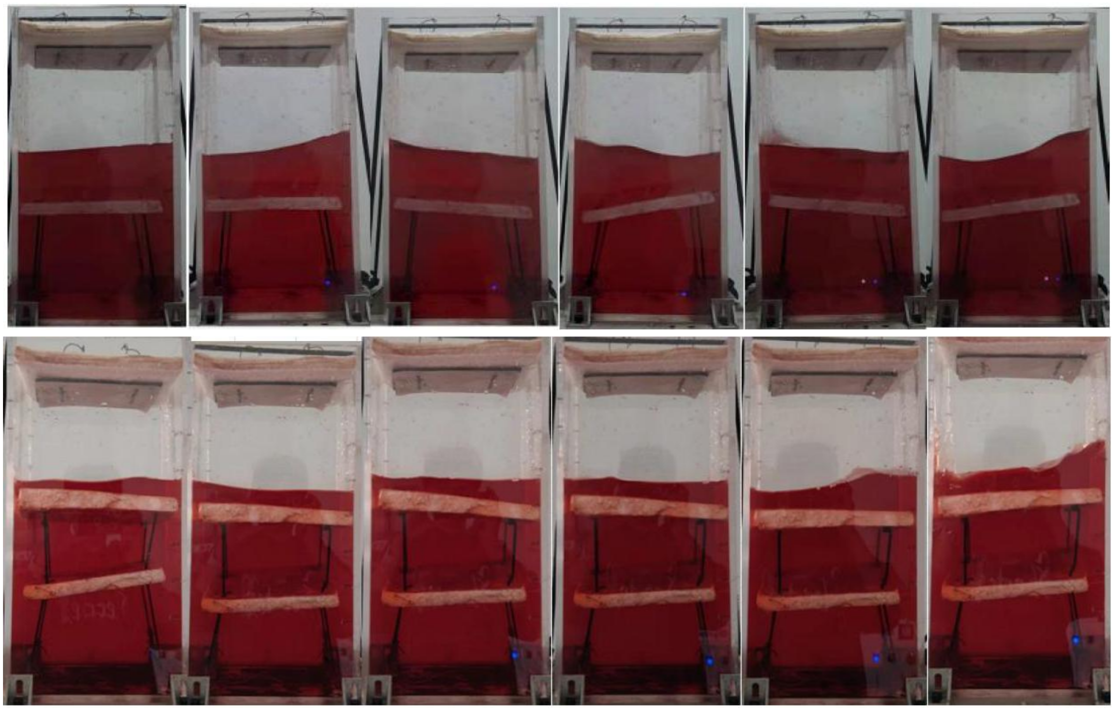
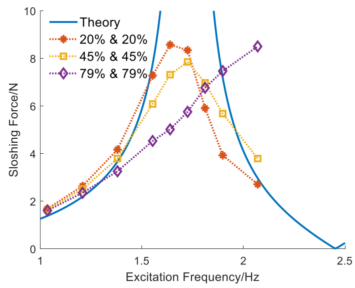


Fig. 3 - Snapshots of free surface (top: single-layer floating plate; bottom: double-layer floating plate; from left to right: 0.7 *f*, 0.8 *f*, 0.9 *f*, 1.0 *f*, 1.1 *f*, and 1.2 *f*)

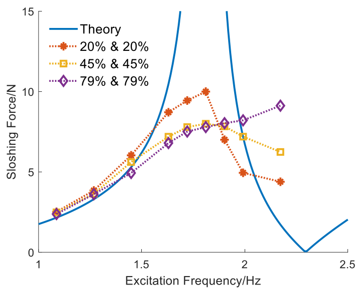
It can be seen that the upper plate of the double-layer floating plate is closer to the free liquid surface than the single-layer floating plate because of larger buoyancy. The sloshing of the liquid above the floating plate can be suppressed by the floating plate and large amplitude sloshing hardly occurs even if at the natural frequency.

The effect of the areas of the floating plate

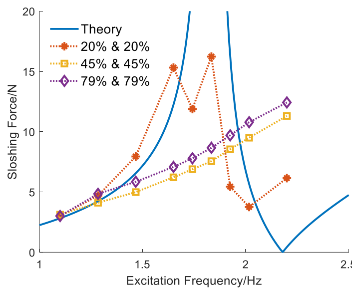
As mentioned earlier, the influence of the plate areas on the sloshing suppression effect of the double-layer floating plate is divided into two cases. The results under the first case are given here. The liquid sloshing force at different depth is shown in Fig. 4 when the areas of two plates change synchronously.



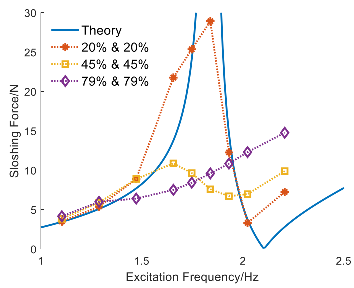
(a) 100 mm



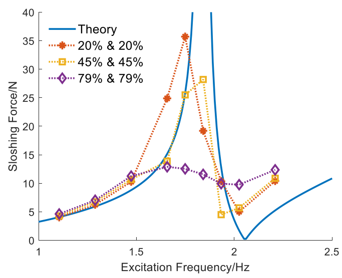
(b) 150 mm



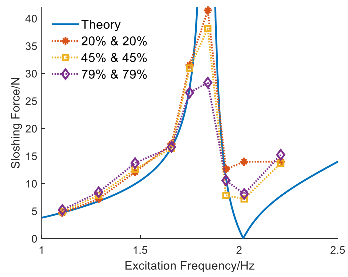
(c) 200 mm



(d) 250 mm



(e) 300 mm



(f) 350 mm

Fig. 4 - Liquid sloshing force at different liquid depths

Apart from the liquid depth of 350 mm, the double-layer floating plate with the largest area ratio (i.e. 79%) shows excellent sloshing suppression performance. Over a wide range of liquid depths, the sloshing force exhibits characteristics of inertial force because the movement of the upper part of liquid is almost completely suppressed by the floating plate.

Comparing the liquid sloshing forces with those of without any plate shown in Fig. 2, it can be got that the double-layer floating plate with the smallest area ratio (i.e. 20%) has good sloshing suppression capability at smaller liquid depths. At the liquid depth of 100 mm, 150 mm and 200 mm, the maximum sloshing force is about 9 N, 10 N and 16 N, reduced by about 40%, 52% and 20%, respectively. However, the sloshing suppression effect almost disappears totally at liquid depths higher than 250 mm. On one hand, smaller plate areas have less impact on the sloshing of the upper free liquid. On the other hand, smaller areas mean less buoyancy from the floating plates, and thus the position of the upper floating plate is lower than that of a larger floating plate. This also reduces the effect of the floating plate on the upper layer of liquid. Therefore, the double-layer floating plate with the smallest area ratio is more likely to fail under larger liquid depth conditions. In other words, the small area of the floating plate is a disadvantage for the liquid sloshing suppression. A larger area is preferred if there is enough space available in the container.

Compared with the floating plate that have the largest area ratio, the double-layer floating plate with the moderate area ratio (i.e. 45%) has relatively weaker liquid sloshing suppression performance when the liquid depth is equal to or greater than 300 mm. The difference of the liquid sloshing force is about 10 N-17 N near the natural frequency. The situation is similar when the liquid depth is 100 mm but the difference is not so significant. It is determined by the fact that the sloshing force of the liquid is relatively small at this depth. However, the situation changes obviously within the range of medium liquid depths (i.e. 150 mm – 250 mm). The sloshing force of medium-sized floating plate is not significantly different from that of large-sized floating plate, especially near the natural frequency. The maximum difference of the sloshing force is less than 5 N. It means that the double-layer floating plate can still effectively suppress liquid sloshing even if the area ratio is less than 50%. This makes it possible to arrange the double-layer floating plate within the limited space of the pesticide container.

The typical wave shapes of the free liquid surface for the double-layer floating plate with the smallest and medium area ratio are shown in Fig. 5. Where, the liquid depth is 250mm and the excitation frequency is also 0.7 f -1.2 f. The waveforms for the double-layer floating plate with the largest area have been shown in Fig. 3, so they are not given again.

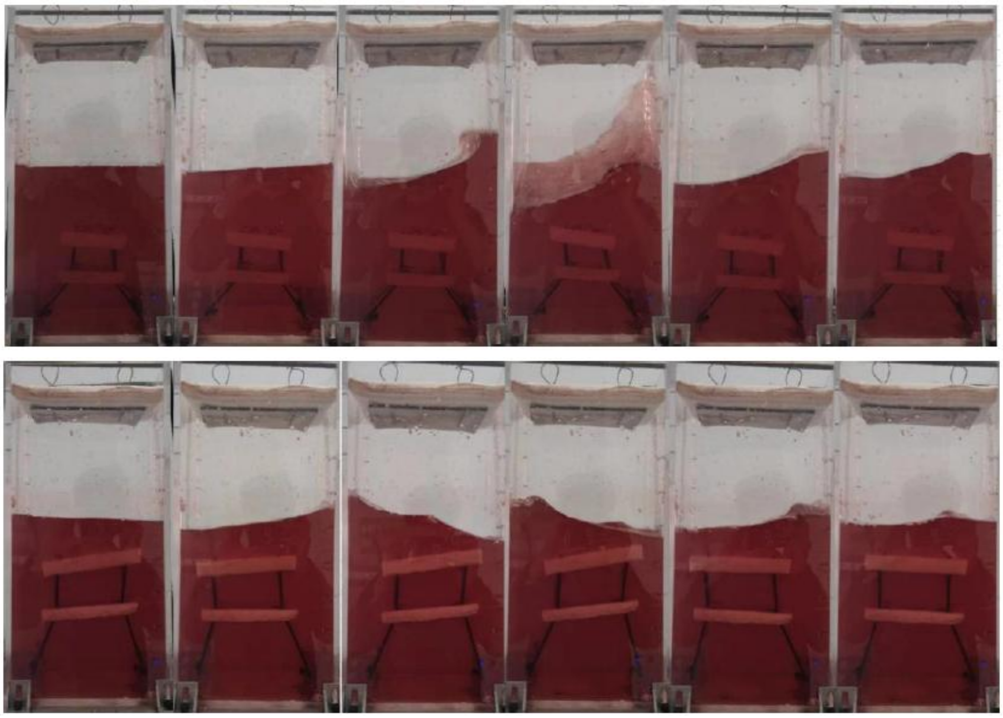
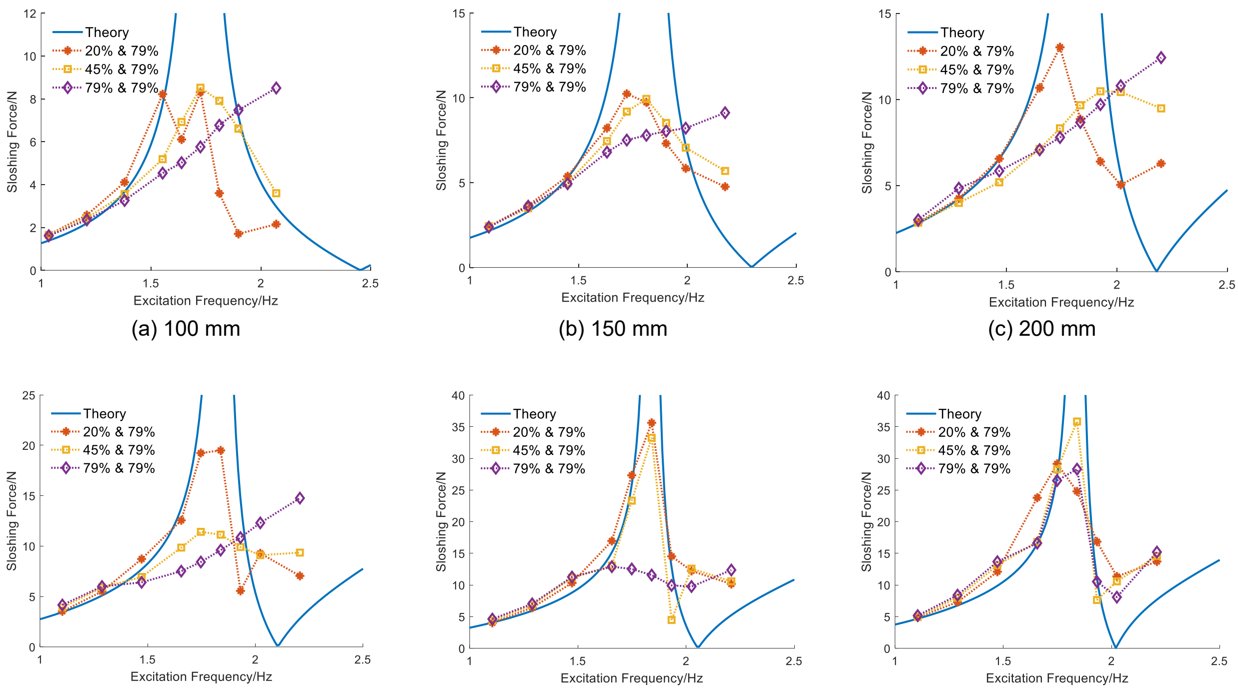


Fig. 5 - Snapshots of the liquid free surface (top: 20% and 20%; bottom: 45% and 45% from left to right: 0.7 f, 0.8 f, 0.9 f, 1.0 f, 1.1 f, and 1.2 f)

It can be seen that the double-layer floating plate with the smallest area ratio exhibits large amplitude sloshing near the natural frequency, which is similar to the case without any plate. However, the situation is much better for the double-layer floating plate with medium area ratio. Although the sloshing amplitude of the free surface is relatively large at 0.9 f and 1.0 f, the sloshing force does not increase significantly.

According to the experimental results above mentioned, the size of the floating plate that is close to the free liquid surface seems to have a greater influence on the sloshing of the liquid. Therefore, the experiment under the second case were further carried out. That is, the upper floating plate keeps the largest area, and the lower floating plate is the smallest or medium area. The liquid sloshing forces at different depths are shown in Fig. 6 when only the area of lower plate changes.



(a) 100 mm (b) 150 mm (c) 200 mm

(d) 250 mm (e) 300 mm (f) 350 mm

Fig. 6 - Liquid sloshing force at different liquid depths

When the liquid depth is equal to 100 mm and 150 mm, the maximum sloshing force for the smallest and medium area lower plate is about 8 N and10 N, respectively. The forces are almost equal to those of both floating plate with the same area. The reason is that only the lower floating plate functions at these liquid depths. The similar situation occurs at the liquid depth of 300 mm and 350 mm. The peak of the sloshing force near the natural frequency means that large amplitude liquid sloshing appears and the sloshing suppression performance of the floating plate decreases to some extent. The largest difference occurs at the liquid depth of 250 mm. The maximum sloshing force is 19 N for the double-layer floating plate composed of areas ratio of 20% (lower layer) and 79% (upper layer), while the maximum sloshing force is 28 N for the double-layer floating plate with the smallest area. This illustrates the role of the upper floating plate area in damping the motion of the upper liquid.

Overall, compared with configurations in which the area ratios of both floating plates were increased simultaneously, increasing only the area of the upper floating plate did not significantly reduce the sloshing-induced force. Moreover, the sloshing force exhibits some unusual changes at certain liquid depths and excitation frequencies. The reason may lie in the change of the direction of the tension of the upper elastic rope, which makes the interaction between the upper floating plate and the liquid more complex. It is necessary to further study its mechanism with the help of numerical simulations and other methods in order to apply the double-layer floating plate in complex situation.

The typical wave shape of the free surface is shown in Fig. 7 where the liquid depth is 250 mm.

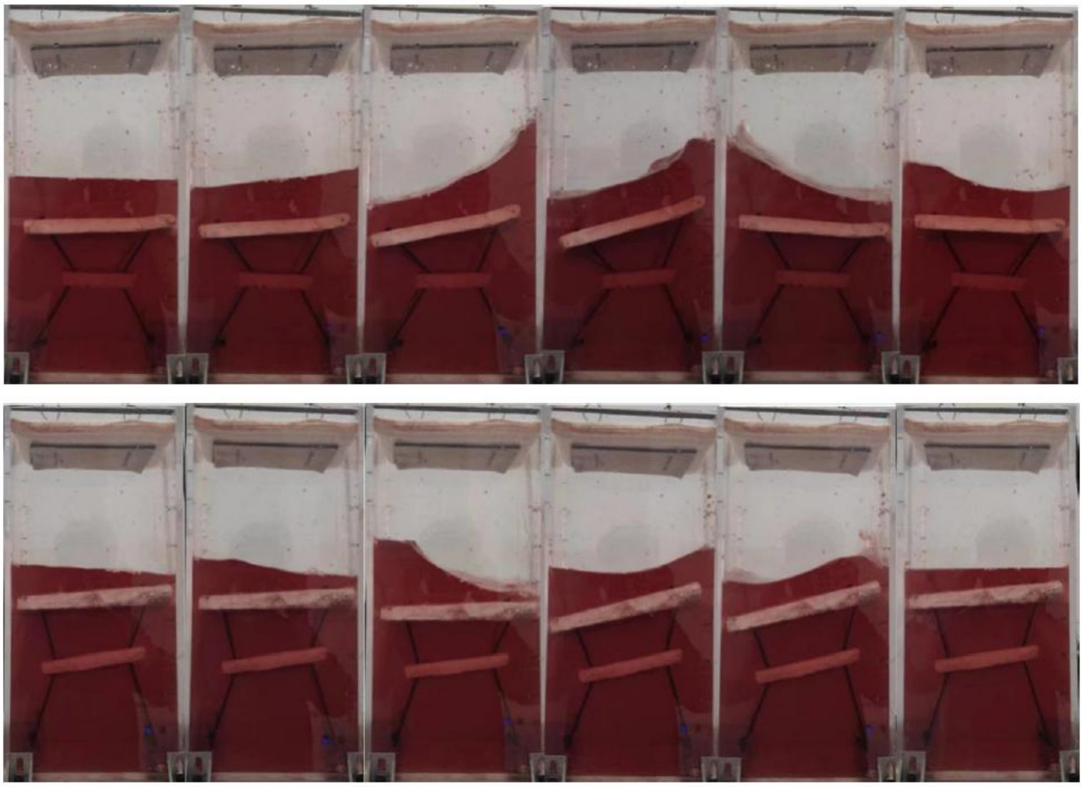


Fig. 7 - Snapshots of the liquid free surface (top: 20% and 79%; bottom:45% and 79%; from left to right: 0.7 f, 0.8 f, 0.9 f, 1.0 f, 1.1 f, and 1.2 f)

It can be seen that large amplitude sloshing occurs near the natural frequency for the area combination of 20% and 79%, while the sloshing amplitude is relatively small for the area combination of 45% and 79%. It is consistent with the changes of the measured sloshing forces shown in Fig.6 (d).

CONCLUSIONS

To improve sloshing suppression in practical applications, a double-layer floating plate was developed based on the single-layer configuration. The effects of the structural parameters of the double-layer floating plate were investigated by measuring the sloshing-induced force at different liquid depths and excitation frequencies. The underlying sloshing-suppression mechanism was also preliminarily examined. The main conclusions are as follows:

(1) The double-layer floating plate provided superior sloshing suppression over a wider range of liquid depths and excitation frequencies.

(2) The medium-sized double-layer floating plate also exhibited effective sloshing suppression at specific liquid depths, indicating its suitability for installation within tanks with limited internal space.

(3) In this study, low- and high-amplitude sloshing conditions were generated by varying the excitation frequency. Both the sloshing-induced forces and the suppression performance of the floating plates were evaluated under steady-state excitation. During actual UAV operation, however, sudden changes in attitude or velocity may produce transient sloshing. Therefore, future work should develop a measurement and data-acquisition system incorporating strain gauges and a microcontroller to capture transient sloshing-induced forces and moments during flight.

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